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Controls on near-surface temperatures across tree line in the Mackenzie Delta area, Northwest Territories, 2004-2009

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ABSTRACT
Air and near-surface ground temperatures were recorded between 2004 and 2009, and properties of the snow cover were measured annually in late winter at eight sites along a 130-km transect across the forest-tundra transition in the uplands east of the Mackenzie Delta, NWT, to investigate the relations between these variables along the ecological gradient. Late winter snow depths decreased along the tree-line transect in association with changes in vegetation cover between sites. A gradient in near-surface ground temperature was observed along the transect, as annual near-surface ground temperatures decreased northward. The ground temperature gradient was steepest (0.1 to 0.3°C/km) between 20 and 30 km from Inuvik. The steep gradient in near-surface ground temperature was associated with large differences in late-winter snow depth between the sites.

1 INTRODUCTION

The position of tree line has a central role in influencing the distribution of permafrost in Canada. The transition between forest and tundra is a significant ecological boundary characterized by variation in the nature of vegetation and snow cover, which strongly influences soil microclimate and permafrost temperatures (Rouse, 1984; Sturm et al., 2001; Kokelj et al., 2007). The consequences of climatic warming in northern Canada (Morrison et al., 2000) may include the northward migration of tree line and an increase in shrubiness of the arctic tundra (Landhäusser and Wein, 1993; Myneni et al., 1997; Sturm et al., 2001). Understanding specific relations between air and ground temperatures across the forest-tundra transition is critical to improve our understanding of how permafrost conditions vary across this gradient and which factors may contribute to future change.

The Mackenzie Delta area is the location of the northern most extent of tree line in Canada. In the uplands east of Mackenzie Delta, the tree-line transition is characterized by a mix of boreal and tundra vegetation often dominated by large shrubs, and occurring as a series of ecological stages, heavily influenced by fire history (Ritchie, 1984; Timoney et al., 1992; Landhäusser and Wein, 1993; Payette et al., 2001; Lantz et al., 2010). Ground temperature conditions have been previously described in several environments of the Mackenzie Delta region (Mackay and MacKay, 1974; Smith, 1975; Burn and Kokelj, 2009; Kanigan et al., 2009;). A large difference in ground temperature has been identified between the boreal forest of Inuvik and tundra communities north of tree line, but detailed information on the transition is sparse in both the Delta and adjacent uplands (Burn and Kokelj, 2009). While relations between vegetation, snow cover, and ground temperature have been studied extensively at the local scale (Mackay and MacKay, 1974; Smith, 1975; Sturm et al., 2001), the relative influence of factors which control ground temperatures across tree line have not been investigated in detail.

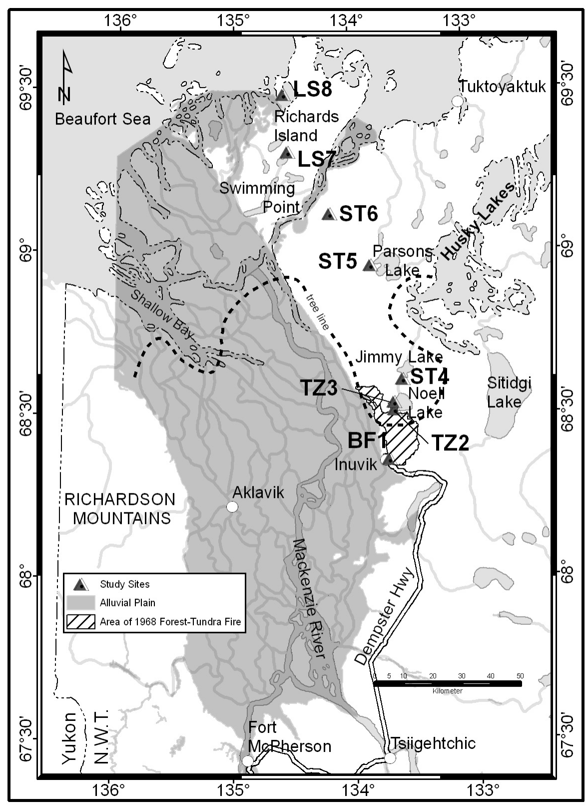

Figure 1 Map of the study area and research sites.

This paper investigates the influence of air temperature, vegetation, and snow conditions on near-surface ground temperatures at several sites across the tree-line transition in the uplands east of Inuvik between 2004 and 2009 (Figure 1). The primary objectives of this paper are: 1) to describe air and near-surface ground temperatures at the study sites across tree line in the uplands east of the Mackenzie Delta; and 2) to investigate the relations between vegetation, snow cover, and ground temperatures at the study sites over the study period.

2 STUDY AREA

Eight sites were selected across the tree-line transition in the uplands east of the Mackenzie Delta area, between Inuvik and Richards Island (Figure 1). Surficial materials, dominated by Quaternary deposits of fine grained glacial tills, are relatively uniform at the study sites (Rampton, 1988). The tills are silty clays with gravimetric moisture contents between 10 and 20%, overlain by an organic layer typically 10-20 cm thick. A north-south gradient in air temperature and precipitation exists across the region, as air temperature and precipitation decrease with proximity to the coast. For the 1971-2000 period mean annual air temperatures at Inuvik and Tuktoyaktuk were -8.8^{o}C and -10.6^{o}C, respectively (Environment Canada, 2010). For the same time period mean total winter snowfall at Inuvik was 168 cm, but only 95 cm at Tuktoyaktuk (Environment Canada, 2010). The regional precipitation gradient is also evident in the mean depth of snow on the ground at the end of March, with 59 cm at Inuvik and 37 cm at Tuktoyaktuk (Environment Canada, 2010).

The study transect extends northward from the subarctic boreal forest around Inuvik to low shrub tundra near the Beaufort Sea coast (Figure 1). All study sites are located on hilltops to limit topographic effects on snow and vegetation distribution. Upland terrain south of Inuvik (BF1) is predominately open boreal woodland populated by black spruce (*Picea mariana*), with an understorey of willow (*Salix* spp.), dwarf birch (*Betula glandulosa*) and alder (*Alnus crispa*) shrubs (Figure 2) (Mackay, 1963; Ritchie, 1984). Near Inuvik, a 500-km^2 area of the forest-tundra transition was burned by an intense fire in 1968 and the northern portion has re-colonized with a dense cover of tall willow, dwarf birch, and alder shrubs 1 to 3 m in height (TZ2) (Figure 2) (Landhäusser and Wein, 1993; Mackay, 1995). In areas north of the burned terrain, the transition zone is characterized by large, widely spaced shrubs, 1 to 2 m in height (TZ3) (Figure 2). In general, the density and size of individual and shrub clusters decrease northward (Lantz et al., 2010). North of the upland transition zone and south of Swimming Point, hilltops are characterized by shrub tundra (ST4-6), which is composed of continuous and discontinuous canopies of deciduous shrubs of dwarf willow, alder and birch up to 0.75 m in height (Figure 2). North of Swimming Point, large alders are found primarily in riparian areas, moist depressions, and stabilized thaw-slump disturbances (Mackay, 1963; Lantz et al., 2009), and hilltops are covered in low tundra vegetation less than 40 cm in height, termed low-shrub tundra (LS7, LS8) (Figure 2).

Figure 2 Biophysical units of the uplands east of the Mackenzie Delta area: A) subarctic boreal forest around Inuvik, B) upland transition zone within the area burned by the 1968 forest-tundra fire, C) upland transition zone 1.5 km north of the 1968 fire limit, D) shrub tundra west of Jimmy Lake, E) shrub tundra west of Parsons Lake, and F) low shrub tundra at Denis Lake, Richards Island.

3 METHODS

To investigate differences in the ground thermal regime across the gradient, air and near-surface temperatures were recorded at seven of the eight research sites between September 2004 and September 2009. Measurements were made every 4 hours with HOBO™ thermistors (Onset Computing, HOBO™, model TMC6-HA) and recorded with 4-channel HOBO™ data loggers (Onset Computing, HOBO™, model H08-006-04). Vegetation height was measured at 5-m intervals along permanently marked 70-m vegetation courses in August 2005. The snow-retention and shading capacity of vegetation is a combination of the structural complexity and the height of the vegetation cover. However, canopy height may be used as a surrogate of canopy complexity, because height closely correlates with complexity in shrub tundra vegetation (Thompson et al., 2004). Snow depth and density was recorded along the vegetation courses at the end of March 2005-2009. Snow depth measurements were made along the 70-m vegetation course at 5-m intervals using a graduated steel probe. Snow density was measured with an Eastern Snow Conference snow sampler at five evenly spaced points along the vegetation course. Sites were visited in a one week period each year and snow fall was less than 5 cm during the period of field sampling.

4 RESULTS AND DISCUSSION

4.1 Relations between vegetation height and late-winter snow depth across tree line

Vegetation height decreased across the transition from subarctic boreal forest to low shrub tundra (Figure 3A). The most abrupt changes in the range and median vegetation heights occurred within 30 km of Inuvik between BF1 and the transition zone sites (TZ2 and TZ3). A large decrease in median vegetation height occurred between TZ2 and TZ3 as a result of distinct differences in vegetation across the 1968 fire limit west of Noell Lake (Figure 1). To the north of the transition zone median vegetation height at the tundra sites was less than 0.5 m. Pair-wise testing indicated significant differences in median vegetation height between all sites except the ST5 and ST6 (χ^2 = 96.0, p = 0.061) (Figure 3A).

Mean snow depths measured in late winter 2005 to 2009 decreased northward from Inuvik (Figure 3B, Table 1). This trend can in part be attributed to the regional gradient in precipitation, for snowfall at Tuktoyaktuk A is only 57% of snowfall recorded at Inuvik A (Environment Canada, 2010). At the LS sites snow depths were 70 and 75 per cent less than at the subarctic boreal site near Inuvik (BF1), demonstrating the loss of snow from low shrub tundra surfaces through redistribution by the wind (Table 1). The significance of snow-vegetation interactions is further illustrated by a 30 to 60 per cent reduction in mean snow depth from the transition zone site (TZ3) to a shrub tundra site (ST4) less than 10 km to the north (Figure 3B; Table 1). In contrast, in several years there was little difference in mean snow depth amongst the upland shrub tundra sites (ST4 to ST6) despite being more than 60 km apart (Figure 3B, Table 1).

A one-way analysis of variance (ANOVA; α = 0.05) was used to investigate differences in mean late winter snow depth amongst BF to ST sites over the 2005 - 2008 period, with the data for all years pooled at each site. Mean late-winter snow depths were not significantly different between sites south of the tree line transition (BF1 to TZ3, P > 0.086) and between ST5 and ST6 (p = 1.000). An additional one-way analysis of variance (α = 0.05) was performed for late winter snow depths from all sites in 2006 in order to include the low-shrub tundra site grouping in the investigation. The results of the ANOVA indicate that there was no significant difference in mean snow depth amongst the LS sites (p = 1.000) and the mean snow depths on the low-shrub tundra were significantly lower than at all the other sites (p < 0.013).

Spearman rank order correlation indicates significant positive associations between snow depth and vegetation height across tree line in all years from 2005 to 2009 ($R_s \geq 0.625$, P < 0.001, N ≥ 103). Figure 4 shows that at sites dominated by shrub vegetation (TZ2-LS8) snow depth increased with the height of the shrubs, however, at the forest site snow depth did not increase with tree height and varied randomly around a mean snow depth of 90 cm. This suggests that the distribution of the snow cover in forests is controlled by factors other than vegetation height. Snow accumulation in forests can

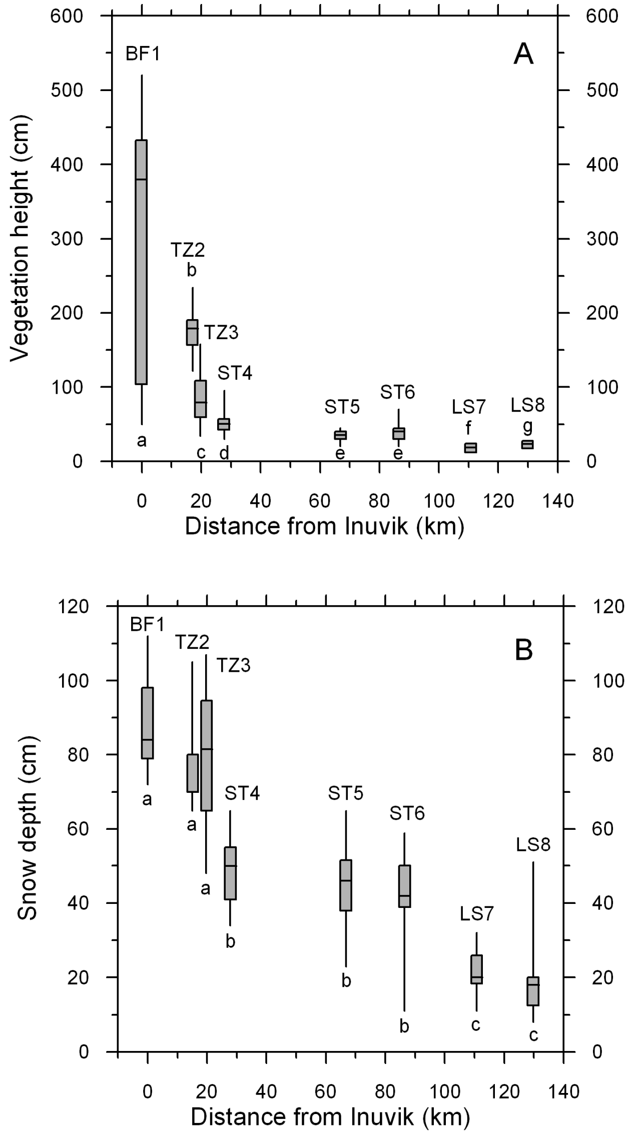

Figure 3 Box and whisker plots for the distribution of: A) August 2005 vegetation height and B) late winter 2006 snow depth across the tree line transition east of Inuvik. In plot A) lower case letters indicate significant differences in median vegetation heights as determined by a Mann-Whitney test of independence, adjusted with the Bonferonni correction. In plot B) lower case letters indicate significant differences in mean snow depth between sites as determined by a one-way analysis of variance (ANOVA, α = 0.05) and the associated Tamhane T2 post hoc test. N = 15 for all sites in both plots. Note that results of the ANOVA in B) is for 2006 late winter snow depth, data is presented in the text for pooled data between 2005 and 2009.

be controlled by leaf area index (LAI) and canopy complexity through interception of the snow cover by the forest canopy (Hedstrom and Pomeroy, 1998; Pomeroy et al., 2002; Kanigan et al., 2009).

Table 1 Annual mean conditions at transect sites 2004-09. All temperature measurements are in °C, TTOP represents the temperature at the top of permafrost recorded at a depth of 100 cm below the ground surface.

	2004-05	2005-06	2006-07	2007-08	2008-09	Range
BF1 (Subarctic boreal)						
Air temperature	-8.3	-7.2	-6.9	-7.8		1.4
Surface temperature	-3.2	-0.8	-1.2	-2.8		2.3
TTOP	-4.0	-3.2	-3.6	-3.6		0.8
Snow depth (cm)	78	89	69	75		20
TZ2 (Transition zone)						
Air temperature	-9.5	-7.9	-8.0	-8.6	-9.6	1.7
Surface temperature	-4.1	-0.3	-2.5	-2.2	-1.7	3.7
TTOP	-4.1	-2.2	-3.1	-3.6	-2.5	1.9
Snow depth	75	80	68	66	81	14
TZ3 (Transition zone)						
Air temperature	-10.5		-8.3	-8.9	-10.0	2.2
Surface temperature	-4.6	-1.0	-3.5	-3.1	-3.0	3.7
TTOP	-4.9	-3.3	-4.0	-4.6	-4.2	1.6
Snow depth	64	83	68	65	82	19
ST4 (Shrub tundra)						
Air temperature	-10.5	-8.4	-8.8	-9.2	-10.4	2.0
Surface temperature	-5.3	-1.1	-3.8	-4.1	-5.0	4.2
TTOP	-5.9	-3.1	-4.8	-4.8	-5.3	2.8
Snow depth	45	50	38	45	35	15
ST5 (Shrub tundra)						
Air temperature	-10.4	-8.4	-8.8	-9.4	-10.2	2.0
Surface temperature	-6.9	-4.7	-5.7	-6.4	-6.2	2.2
TTOP	-6.5			-6.4	-6.3	0.2
Snow depth	37	45	24	39	33	21
ST6 (Shrub tundra)						
Air temperature	-10.8	-9.2			-10.6	1.6
Surface temperature	-6.7	-4.6		-7.0	-7.3	2.8
TTOP	-6.5	-5.2		-6.6		1.4
Snow depth	31	42	32	38	27	15
LS7 (Low shrub tundra)						
Air temperature						0.0
Surface temperature		-5.4	-5.5	-5.9		0.5
TTOP		-6.1	-6.3	-6.4		0.3
Snow depth		22	20	23	25	5

These data are consistent with previous studies (e.g., Pomeroy et al., 1995; Essery et al., 1999; Essery and Pomeroy, 2004; Pohl and Marsh, 2006; Pomeroy et al., 2006), which showed large differences in snow loading between tall and low-shrub ecological landscapes due to the lower snow retention capacity of low-shrub vegetation. Several of these studies also highlight the importance of mesoscale wind exposure and relocation of snow in controlling the depth of snow within the forest-tundra transition (Pomeroy et al., 1995; Essery and Pomeroy, 2004). Largest snow depths are often

observed in tall-shrub landscapes close to low-shrub tundra, because once vegetation at low-shrub landscapes fills with snow, additional snow is available to be redistributed to nearby areas with greater retention capacity, including topographic lows and areas of taller shrubs. In this study large differences in maximum snow depth were recorded between TZ3 and ST4 (Figure 3B), as TZ3 fringes shrub tundra on the west side of Noell Lake, and may be a destination for regionally redistributed snow.

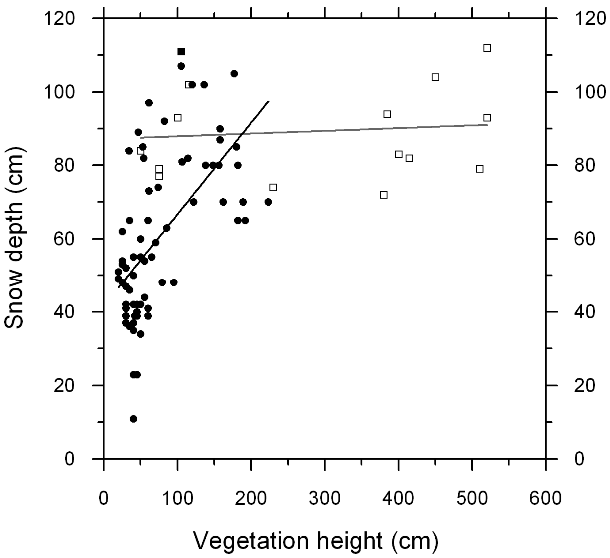

Figure 4 March 2006 snow depth (cm) and vegetation height (cm) measured along the snow courses at all sites (BF1-LS8). Least squares regression lines are plotted for the forest site (□) ($y = 0.007x + 87.128$; $r^2 = 0.01$; $P = 0.71$; $N = 15$) and sites north of the forest (●) ($y = 0.35x + 27.32$; $r^2 = 0.49$; $P < 0.001$; $N = 102$).

4.2 Thermal properties of the snow cover

The thermal insulation quality of the snow cover is expressed as thermal resistance (R_s; m^2 K W^{-1}), and is controlled by the thermal conductivity (λ_s; W m^{-1} K^{-1}) and the thickness of the snow layer (ΔH; m):

$$R_s = \frac{\Delta H}{\lambda_s}$$ [1] (Lunardini, 1981)

Where the thermal conductivity of snow (for density, $\rho < 0.60$) can be estimated using:

$$\lambda_s = 10^{(2.650\rho - 1.652)}$$ [2] (Sturm et al., 1997)

Table 2 presents estimates for the thermal conductivity and thermal resistance of the snow pack at sites BF1 to LS8. It is interesting to note that there was little variation in the density of the overall snowpack between sites. This is likely because at sites with low snow cover the depth-hoar layer represented 40 to 50% of the snow pack, compared to 25-35% at sites with a deeper snow cover. An increase in the proportion of depth hoar in the snow pack reduces the overall bulk density of the entire snow profile (Zhang et al., 1996; Sturm and Benson, 1997). Thermal resistance of the snow pack was largest at sites BF1 to ST4 (11.4 to 7.8 m^2 K W^{-1}). North of ST4 the thermal resistance of the snow pack was lower (6.9 to 2.7 m^2 K W^{-1}). This shows that the snowpack at low shrub tundra sites is most conducive to ground heat loss in winter.

Table 2 Thermal properties of the snow cover at the end of winter 2005, 2006, 2008.

	Mean snow density (g cm^3) (N= 15)	Thermal conductivity[a] (W m^{-1} K^{-1})	Mean snow depth (m) (N=45)	Thermal resistance (m^2 K W^{-1})
BF1	0.19	0.071	0.81	11.4
TZ2	0.22	0.083	0.74	8.9
TZ3	0.23	0.091	0.71	7.8
ST4	0.12	0.046	0.47	10.2
ST5	0.16	0.058	0.40	6.9
ST6	0.19	0.071	0.37	5.2
LS8	0.24	0.095	0.26	2.7

[a]Estimated from Sturm et al. (1997)

4.3 Air and near-surface ground temperatures

Annual mean air temperature decreased across the tree-line transition (Table 1) and temperatures at ST6 were generally 2°C lower than at BF1. Burn (1997) demonstrated that a steep gradient in air temperature exists in the region particularly during early summer when onshore winds blow off of the sea ice and cool coastal areas. In winter, conditions are more uniform as the land and sea are snow covered (Burn, 1997). Our data confirms that air temperatures were relatively similar among the sites during winter, but during summer the air temperatures increased with distance from the coast (Figure 5B). In general, winter conditions likely exert a greater influence on the ground thermal regime than summer conditions as the ratio of freezing degree days to thawing degree days in the air is roughly 4:1 along the study transect.

Near-surface ground temperatures decreased northward across the tree-line transition and annual mean surface temperatures were 3°C – 4.5°C lower in the low-shrub tundra environment (LS7) than in the boreal forest around Inuvik (BF1) (Table 1). These differences were reflected at depth, where annual mean temperatures at the top of permafrost in tundra environments were generally 3°C lower than in the boreal forest and transition zone. Most of the variation in annual mean surface and top of permafrost temperature occurred over a distance of 50 km between TZ2 and ST5 (Table 1). In most years differences of 1°C to 3°C in surface and top of permafrost temperatures occurred between the transition zone (TZ2 and TZ3) and the shrub tundra at

Jimmy Lake (ST4), across a distance of only 10 km (Table 1). This implies a 0.1 to 0.3°C/km change in near surface ground temperature between TZ2 and ST4 compared to a rate of 0.01 to 0.06°C/km over 60 km between ST4 and ST6. This variation in near-surface ground temperature corresponds with a large difference in mean and maximum snow depth.

Daily surface temperatures were similar between sites during summer and began to diverge in fall with the arrival of the snow cover, especially once sites had overcome latent heat effects in the soil (Figure 5B). Differences in daily surface temperature persisted throughout winter until the disappearance of the snow cover in May (Figure 5B). The Pearson product moment correlation between annual mean surface temperature and mean late-winter snow depth indicated that there was a significant positive association between the two variables ($r = 0.820$; $P < 0.001$; $N = 32$) (Figure 6). These data suggest that differences in the ground thermal regime across tree line are controlled by winter conditions, in particular differences in snow conditions.

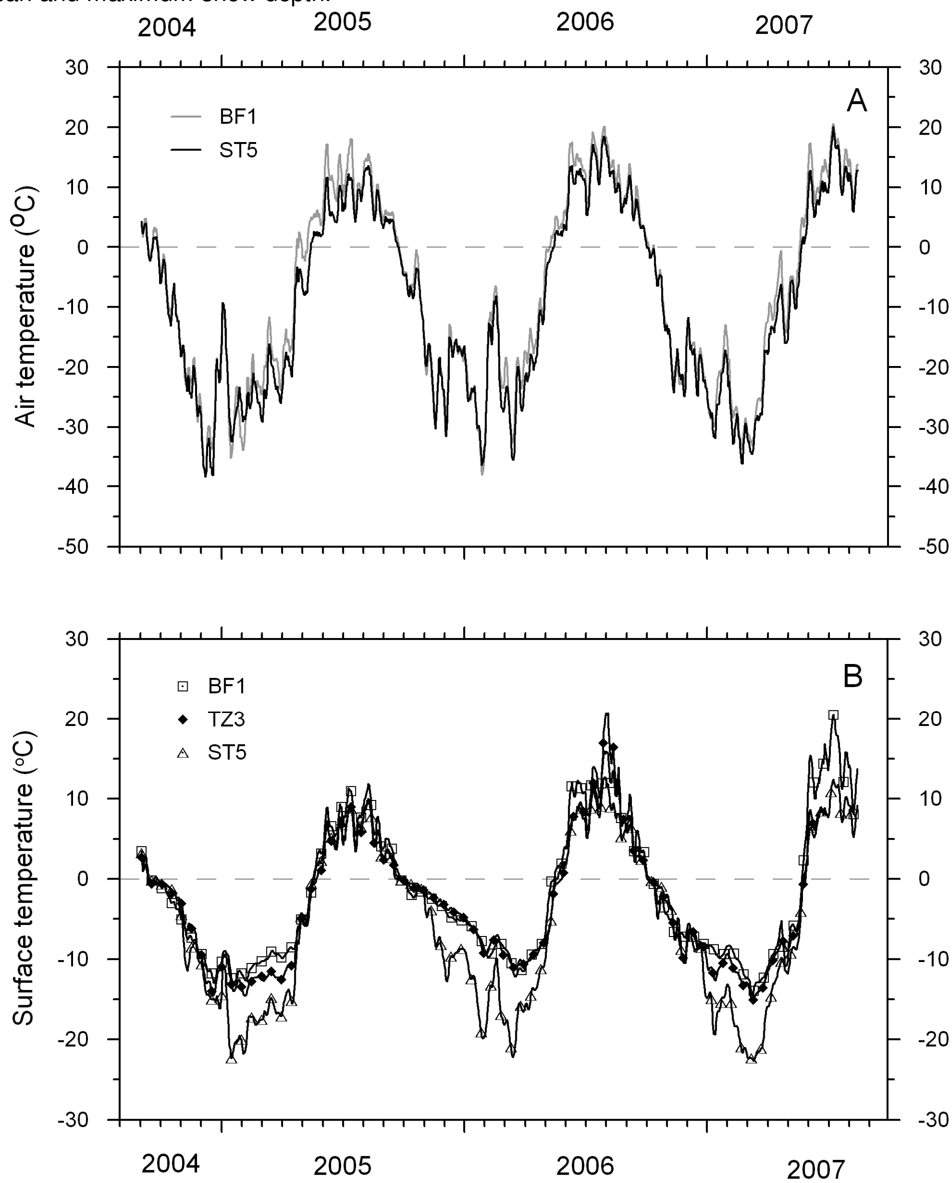

Figure 5 Daily A) mean air temperature at BF1 and ST5 and B) mean surface temperature at BF1, TZ3, and ST5 September 1, 2004 to September 1, 2007. The air temperature regimes for sites TZ2, TZ3, and ST4 lie within the regimes of BF1 and ST5, therefore, for clarity only the air temperature regimes at BF1 and ST5 are presented. Air temperatures were recorded every 4 hours, but the lines represent 5-day running means. Symbols in plot B are presented every 15 days, and the plot is continuous throughout the year.

In the uplands east of the delta, transition zone snow depths are comparable to conditions in the subarctic boreal forests and are significantly greater than on the shrub tundra. Our field data suggest that anticipated future climate warming and potential greening of tundra environments in the Mackenzie Delta region will lead to increased snow cover in shrub tundra settings, in particular where structurally complex vegetation was previously absent. Enhanced snow accumulation will lead to warmer ground temperatures and the impact of warming associated with increased shrubiness of the tundra may compound warming associated with expected rising air temperatures. The magnitude and timing of early season snow fall and the evolution and duration of the snow cover also have a

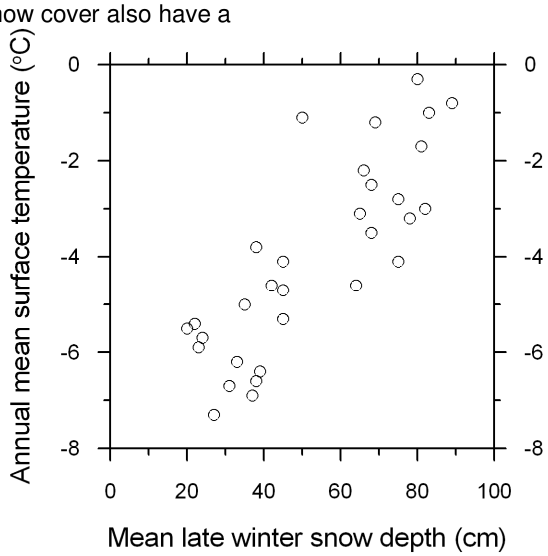

Figure 6 Annual mean surface temperature and mean late winter snow depth at all sites between 2004 and 2009. Pearson product moment correlation indicates a significant positive association between the two variables ($r = 0.820$; $P < 0.001$; $N = 31$).

considerable influence on the ground thermal regime, in addition to the late winter snow depth (Rouse, 1984; Ling and Zhang, 2003). Variation in these properties of the snow pack may explain some of the differences in near-surface ground temperatures when late season snow depths were similar (Table 1) and should be explored for this region in the future.

5 CONCLUSIONS

The following three conclusions can be drawn from the examination of the relations between vegetation, snow cover, and air and near-surface ground temperatures at the study sites across tree line presented in this paper:

(1) Snow conditions at the study sites were controlled by interactions with the vegetation cover at the sites. Larger snow depths were associated with taller, more structurally complex vegetation.

(2) A gradient in ground temperature exists in the region and annual mean ground temperatures decreased northward across the tree line transition. The ground temperature gradient was steepest (0.1 – 0.3°C/km) between Noell Lake and Jimmy Lake.

(3) The ground temperature gradient across tree line in the region was predominately controlled by winter conditions and large differences in ground temperature between sites were associated with large differences in late winter snow depth in the region.

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